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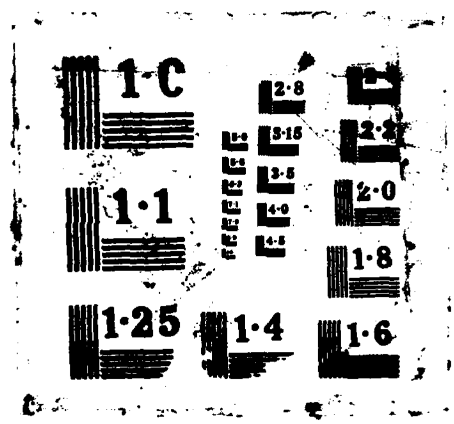
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report identified and characterized mathematically the various error components associated with lines of bearing (LOB's). The most general case was assumed. The error categories considered were: Sensor platform position errors, sensor platform orientation errors, sensor attitude errors, antenna errors, instrumentation errors, and timing errors.

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EXTENDED ALGORITHM ANALYSIS FAMILY EAAF

I/EW SENSOR ERROR BUDGET FOR DF FIX ESTIMATIONS

EAAF

Technical Memorandum No. 4

August 14, 1985

by

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JET PROPULSION LABORATORY
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ERROR BUDGET

1.0 PURPOSE

The purpose of this document is to identify all of the various error components, in the most general case, when determining lines of bearings. These lines of bearing are used in subsequent fix estimations for emitters.

2.0 SCOPE

The essential assumptions of this document are: the emitter is not moving at the time the line of bearing is measured; the sensor may be in any position, from earth bound to a moving satellite; if the emitter is moving, it is moving at a constant speed in one direction at the instant of the line of bearing measurement.

The type of errors considered may be classified into several categories:

Sensor platform position and orientation errors;
Sensor attitude;
Antenna errors;
Instrumentation errors; and
Time.

The sensor platform position and orientation errors may be referred to as "positional errors".

Errors due to propagation effects, site selection, varying aperture versus aspect effects, and operator errors are not considered in this document. Also, errors due to the choice of algorithms or numerical computations are not considered.

3.0 POSITIONAL ERRORS OF A PLATFORM

The geocentric coordinates and references are:

Latitude	ϕ	Phi
Longitude	θ	Theta
Altitude	h	

Orientation of meridian plane(Direction of North)

These coordinates are best described by the diagram in figure 1. The geographic latitude is measured positive from the equator towards the North Pole in degrees. The geographic longitude is measured positive from the prime meridian at Greenwich towards the East in degrees. The altitude is measured from the mean sea level(the geoid) in meters and is positive in a direction away from the center of the earth. The physical sources of errors in these parameters will depend largely on the source of the data used to determine them.

3.1 Cartographic errors:

The circles of longitude and latitude may be transformed by projections onto planes, cones or cylinders thus forming military maps(see reference 1). A map is a source for a multitude of potential errors. These errors depend on the how the map is used. Errors in visual bearings, measured with the aid of a map, encompass all of the potential errors that concern this report. Also the spherical aberations due to projecting the surface of a sphere onto a two dimensional surface adds to the potential errors that concern this report. Features of a map are usually represented by lines and symbols that are larger than the features they represent. Map makers commonly over simplify complex features e.g., very curvey roads and isobars of contour. Visual bearings and radio compass bearings are always used in conjunction with a map. Loran(long range radio navigation) is always used with maps containing the hyperbolic lines of equal light time differences between pairs of special fixed-base transmitters. Tacan (tactical air navigation) is a UHF polar coordinate navigation system using a pulse technique to determine the distance from the ground station. The ground station then uses a rotating antenna to obtain both course and fine bearing information. This Tacan position estimate is then referenced to a map to find a final position estimate.

3.2 Geodetic errors:

The the shape of the earth, excluding the land masses, is called the "geoid". The geoid may be defined as an equal potential surface about the mean level of the oceans where the direction of gravity at every point is perpendicular to the surface. Because the earth's shape is almost an oblate spheroid, the intersections of the "great circles" of longitude are close to the shape of ellipses. Because of variations in the density of the earth's constituants and the irregularity of their distribution, the geoid generally rises over continents and is depressed in oceanic areas. It also shows various other bumps and hollows that depart from an "average smoothness" by as much as 60 m (see reference 3, page 34). The oblateness of the spheroid shows a difference between the astronomical latitude and the geocentric latitude (see figure 3) which is about 11 minutes of arc (20 km) at its maximum in the vicinity of the forty fifth parallel (see reference 4). Because of these eccentricities, great effort must be expended so that determinations of position will be consistent everywhere.

Field soldiers and mobile units often have to depend on magnetic compasses for determining bearings. Although this is one of the oldest means of taking bearings, it can be very inaccurate. The compass tends to point almost towards the nearest magnetic pole. However the magnetic poles are about three kilometers from the geographic poles. Furthermore, the two poles, North and South, are not even symmetrically placed. And to complicate this, there are local variations over all the earth's surface. This angle that the compass makes with the true geo-

graphic meridian is called the "declination" of the compass. The declination at any one location does not remain the same year after year and changes somewhat over long periods of time. Besides these so-called secular changes, there are variations within the year and also small changes of angle throughout the day. Large erratic variations occur during "magnetic storms". These storms are often concurrent with the appearance of sunspots.

Variations from storms are infrequent enough and the other variations are sufficiently slow that it is practical to publish maps of countries and other large areas showing the magnetic declination. On these maps, points of equal magnetic declination are connected by lines. Each wiggly line is labeled with the amount and direction of the magnetic declination. These lines are called isogonic lines. The isogonic line of zero magnetic declination is indicated by a heavy line, and is called the agonic line. Maps of smaller area indicate the magnetic declimation in their legend by an arrow pointing to the magnetic north and labelled with the value of the magnetic declination in degrees. The magnetic lines of force are not parallel to the earth's surface, except along the indefinite circle called the magnetic equator. The angle the magnetic field makes with a horizontal plane is called the dip angle or the magnetic inclination.

3.3 Inertial navigation:

The four coordinates of position can be maintained by a suitably designed inertial platform. There will be essentially three types of errors: the basic resolution of the inertial platform; the accuracy of the initialization; and the rate of drift. Time becomes a critical factor because of this drift.

4.0 ATTITUDE ERRORS

The three attitude coordinates are:

Roll Angle	α	alpha
Pitch Angle	β	beta
Yaw Angle	γ	gamma

Figure 2 serves to define each of these angles. These are the standard Euler angles as defined by a "right hand" rule. However it should be noted that the sign of these angles vary considerably throughout published literature. See Korn and Korn, reference 2, section 14.10-6, for a discussion of this coordinate system and the diverse choice of signs. In some airborn systems these positional coordinates are limited by preset stops which may introduce non-linear errors.

4.1 Correlations between attitude and positional coordinates:

With a cursory examination of these six coordinates, it is apparent that errors in three of them will produce the larger errors. An error in yaw angle alone will produce a divergence of the azimuth angle of bearing. This azimuth error will always be

quite close in magnitude, but opposite in sign, to the Yaw error. Errors in longitude and latitude will produce an error in the position of the line of bearing as a function of the azimuth angle, but this does not effect the azimuth angle. If the azimuth angle is in the vicinity of zero or 180 degrees, an error of longitude will be reflected directly, and of nearly the same value, in the longitude of the fix estimations. At azimuth angles of 90 and 270 degrees, the line of bearing and consequently the fixes are unaffected by errors in longitude. The effects of errors in latitude are analogous in their effect but displaced by 90 degrees.

It is not so obvious that an error in the three remaining coordinates(altitude, roll, and pitch) should have any effect on the line of bearing. Indeed an error in altitude alone should only change the slant range and have no effect on the line of bearing. However when coupled with errors in roll and pitch, there is a definite mathematical relation or coupling. The significance of an error in altitude remains to be evaluated. Errors in roll and pitch(which have less effect on the error of the fix estimate than yaw, longitude and latitude) directly cause errors in azimuth angle on the line of bearing.

5.0 ANTENNA ERRORS

Orientation with respect to the platform
Difference between the mechanical axis and RF axis
Beam width

These two antenna errors are directly related to the platform attitude coordinate errors. In fact the orientation of the antenna with respect to the platform and the difference between the mechanical axis and the RF axis are best described by Euler angles. If the axis defining these coordinates are chosen originally in coincidence, first order approximations will serve to considerably simplify the maze of trigonometric functions relating these angles. These three Euler angles can be identified as pitch, roll and yaw. For small errors in these angles, the errors may be simply added to the corresponding platform angles. It should be noted at this point that the RF boresight error is a function of the radio frequency.

Beam width is always a function of the antenna geometry and frequency. A phased antenna system's beam width will vary considerably with change in aspect angle.

6.0 INSTRUMENTATION ERRORS

Bias (Systematic errors)
Noise (Random errors)

Bias errors are systematic errors such as boresite errors, parallax errors in instrument readings, and bezel errors for example. Bias errors are usually minimized by calibration procedures.

Noise errors are due to random phenomenon such as receiver noise. This noise normally produces random errors in bearings by increasing the region of uncertainty when determining the minima of a signal or the change in sign from the phase of a signal. There are many techniques of minimizing the effects of noise depending on the source and nature of the noise(see reference 5). In high frequency receivers, the receiver's "front end" is a high source of thermal noise, so the high gain required is usually obtained after heteradyning to a lower frequency or after further detection at the "rear end". Commonly the band pass of filtering is reduced to the minimum that will not deteriorate the information content. The effect of impulse noise such as noise emanating from electrical ignitions can be minimized by amplitude clipping just above the signal level.

7.0 ERROR TABULATION

The items in the "TABULATION OF ERROR BUDGET" are listed in order of priority as a reference when possible. The more important, accurate, or reliable items are listed first. For example, in an airborne sensor, the pilot depends on the inertial platform to contol the aircraft. However he will continuously monitor the inertial platform by checking his other more conventional flight instruments such as altimeters and attitude sensors. Periodically the pilot will make reference to a map.

The specifications and tolerances will always include the units. The exact meaning of the specification and tolerance columns will depend on the instrument involved.

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TABULATION OF ERROR BUDGET

CLASSIFICATION	SPECS	TOLER
FIXED SENSORS		
1. Station positional errors		
a. Longitude		
b. Latitude		
c. Altitude		
d. Reference meridian(North)		
2. Antenna errors		
a. Mechanical orientation		
b. Difference between mechanical axis and RF axis		
3. Instrument errors		
a. Bias (systematic or secular arrors)		
b. Noise random errors		
MOBILE AND PORTABLE SENSORS		
1. Cartographic		
a. Longitude		
b. Latitude		
c. Altitude		
2. Bearings		
a. Magnetic compass		
b. Radio direction finder		
AIRBORNE SENSORS		
1. Inertial platform		
a. longitude		
b. latitude		
c. altitude		
d. True North		
e. Roll		
f. Pitch		
g. Yaw		
h. Rates(TBD)		
2. Altimeters		
a. Barometric		
b. Radio		
3. Compass		
a. Gyro-compass		
b. Radio compass		
c. Magnetic compass		
4. Attitude sensors		
a. Needle and ball (turn and bank indicator)		
b. Artificial horizon		
c. Situation indicator		
5. Cartographic		
a. Longitude		
b. Latitude		
c. Altitude		

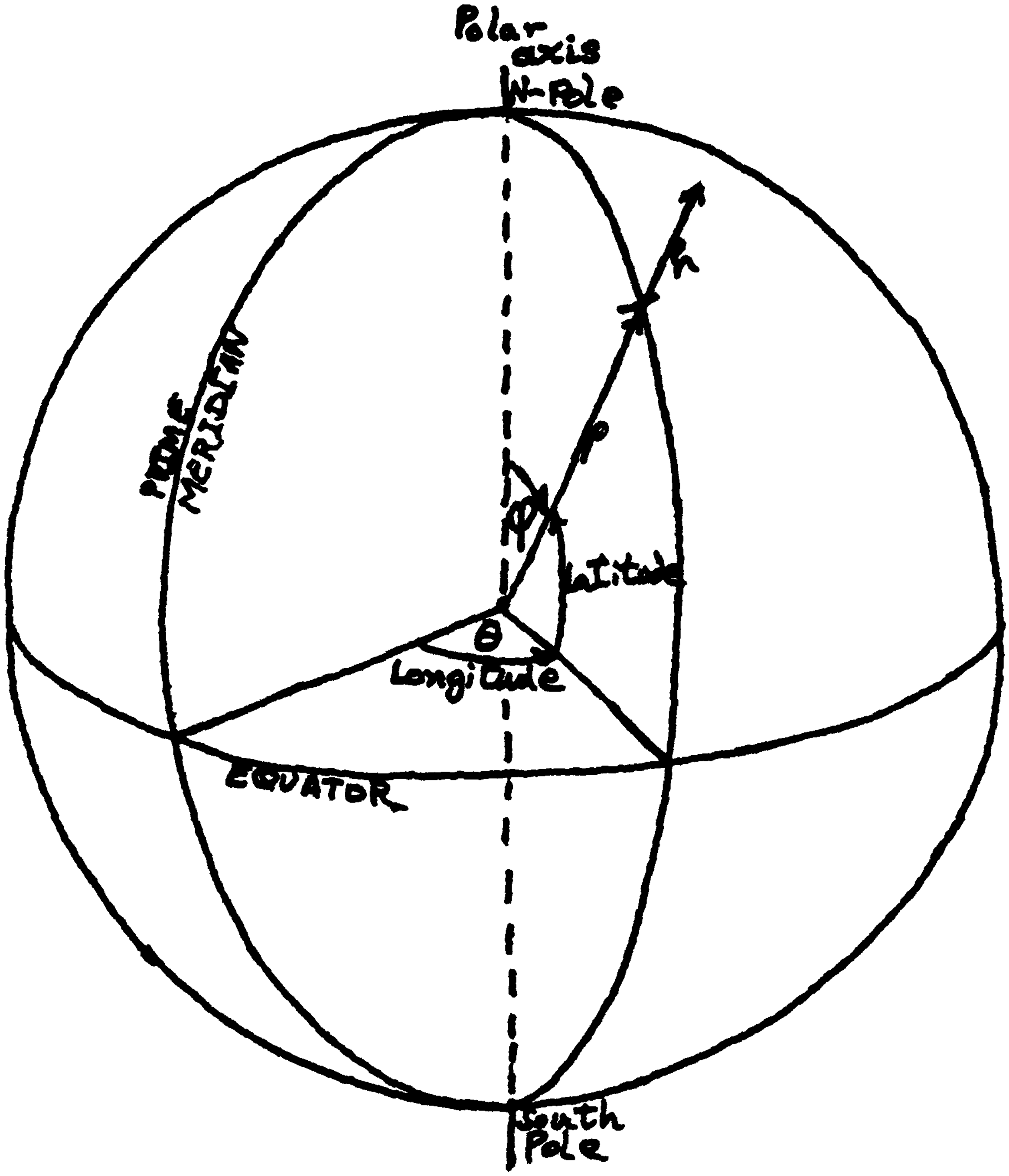

Figure 1. Geocentric Positional Coordinates.

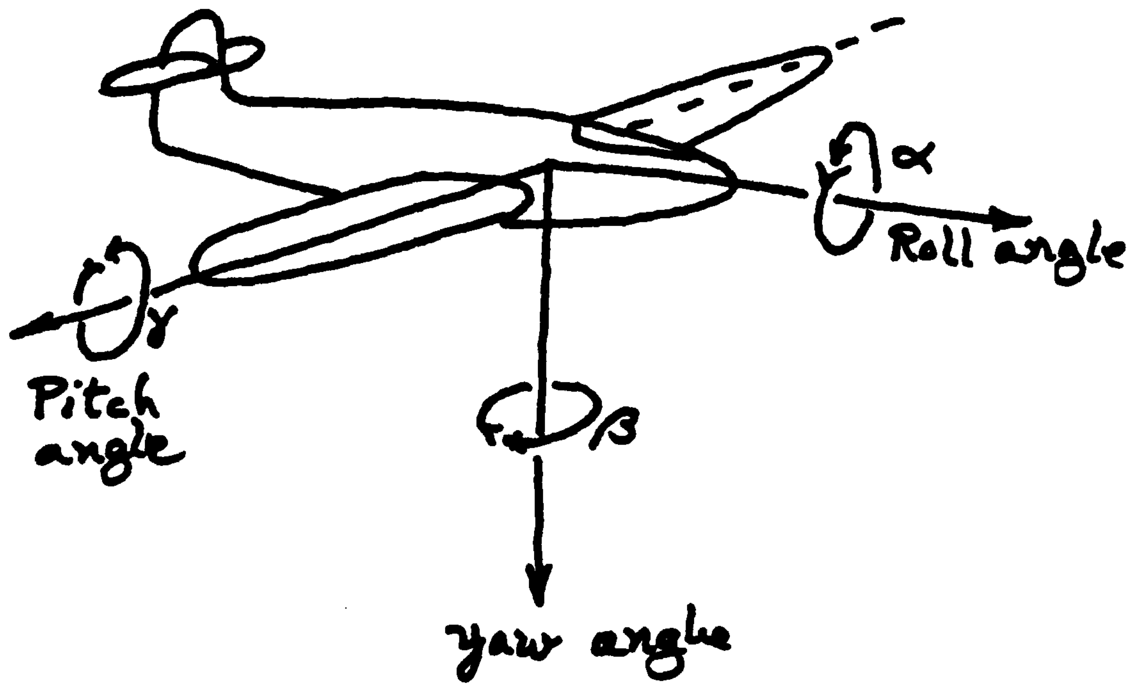

Figure 2. Attitude of the platform.

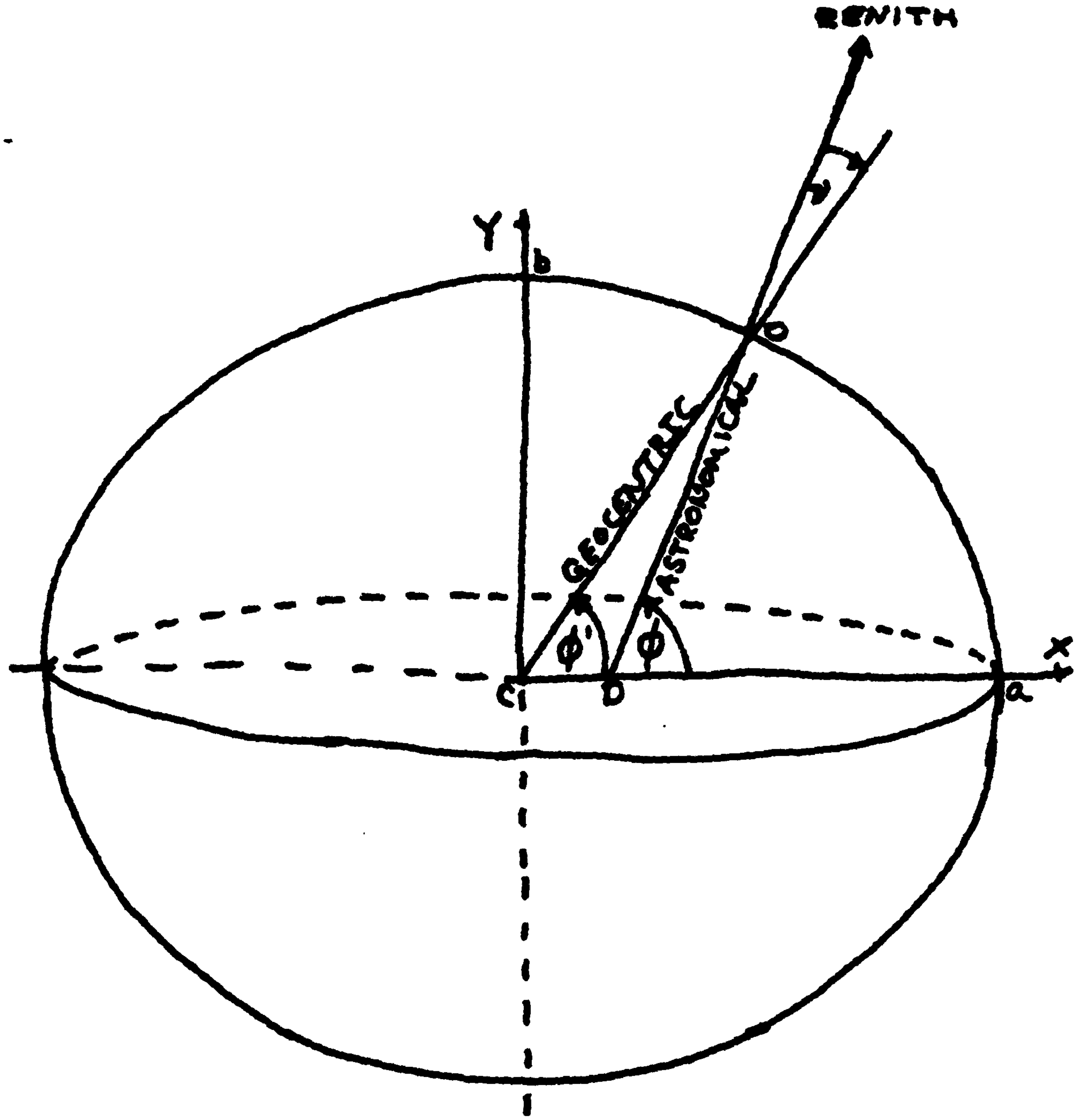

Figure 3. The Geoid and Latitude.

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